US009122697B1

(12) **United States Patent**
Bono et al.

(10) **Patent No.: US 9,122,697 B1**
(45) **Date of Patent: Sep. 1, 2015**

(54) UNIFIED DATA SERVICES FOR BLOCK AND FILE OBJECTS

(71) Applicant: **EMC Corporation**, Hopkinton, MA (US)

(72) Inventors: **Jean-Pierre Bono**, Westborough, MA (US); **William Davenport**, Burlington, MA (US); **Miles A. de Forest**, Bahama, NC (US); **Philippe Armangau**, Acton, MA (US); **Walter C. Forrester**, Berkeley Heights, NJ (US); **Karl Owen**, Chapel Hill, NC (US)

(73) Assignee: **EMC Corporation**, Hopkinton, MA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 196 days.

(21) Appl. No.: **13/853,284**

(22) Filed: **Mar. 29, 2013**

(51) **Int. Cl.**
G06F 17/30 (2006.01)

(52) **U.S. Cl.**
CPC ***G06F 17/30194*** (2013.01); *G06F 17/30091* (2013.01)

(58) **Field of Classification Search**
None
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

2004/0030668	A1*	2/2004	Pawlowski et al.	707/1
2009/0055556	A1*	2/2009	Lachmund et al.	710/11
2010/0094847	A1*	4/2010	Malan et al.	707/705
2010/0306500	A1*	12/2010	Mimatsu	711/209
2014/0229440	A1*	8/2014	Venkatesh et al.	707/634

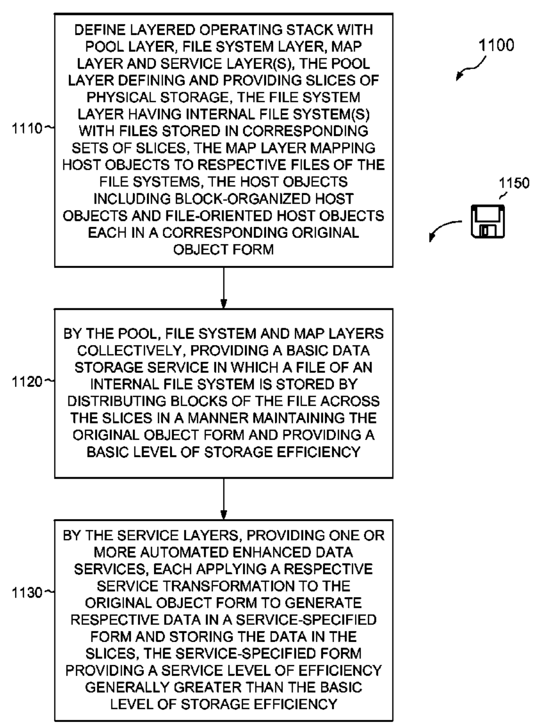
* cited by examiner

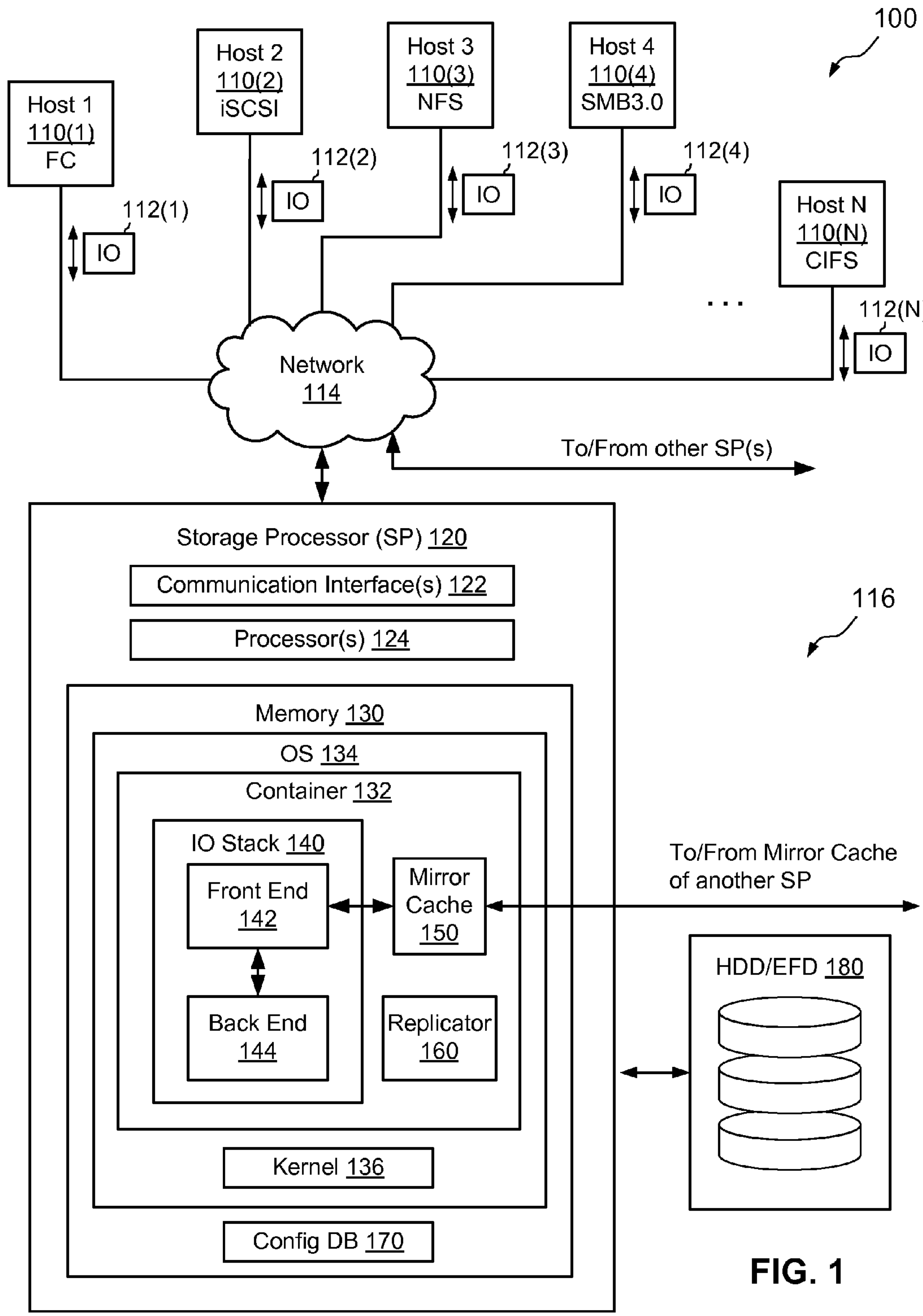
Primary Examiner — Hung Q Pham
(74) *Attorney, Agent, or Firm* — BainwoodHuang

(57) **ABSTRACT**

An improved technique for a data storage apparatus that combines both block-based and file-based functionality in a unified data path architecture. The improved technique brings together IO processing of block-based storage systems and file-based storage systems by expressing both block-based objects (e.g., LUNs) and file-based objects (e.g., host file systems) in the form of files. These files are parts of an underlying set of internal file systems stored on a set of storage units served by a storage pool. Because block and file-based objects are all expressed as files of this set of internal file systems, a common set of services can be applied across block-based and file-based objects. In particular, enhanced data services such as compression, automated storage tiering and deduplication are provided across both types of object using one set of common mechanisms.

26 Claims, 10 Drawing Sheets





100
Host 1
110(1)
FC
Host 2
110(2)
iSCSI
Host 3
110(3)
NFS
Host 4
110(4)
SMB3.0
Host N
110(N)
CIFS
112(1)
IO
112(2)
IO
112(3)
IO
112(4)
IO
112(N)
IO
. . .
Network
114
To/From other SP(s)
Storage Processor (SP) 120
Communication Interface(s) 122
Processor(s) 124
116
Memory 130
OS 134
Container 132
IO Stack 140
Front End
142
Back End
144
Mirror
Cache
150
Replicator
160
To/From Mirror Cache
of another SP
HDD/EFD 180
Kernel 136
Config DB 170

FIG. 1

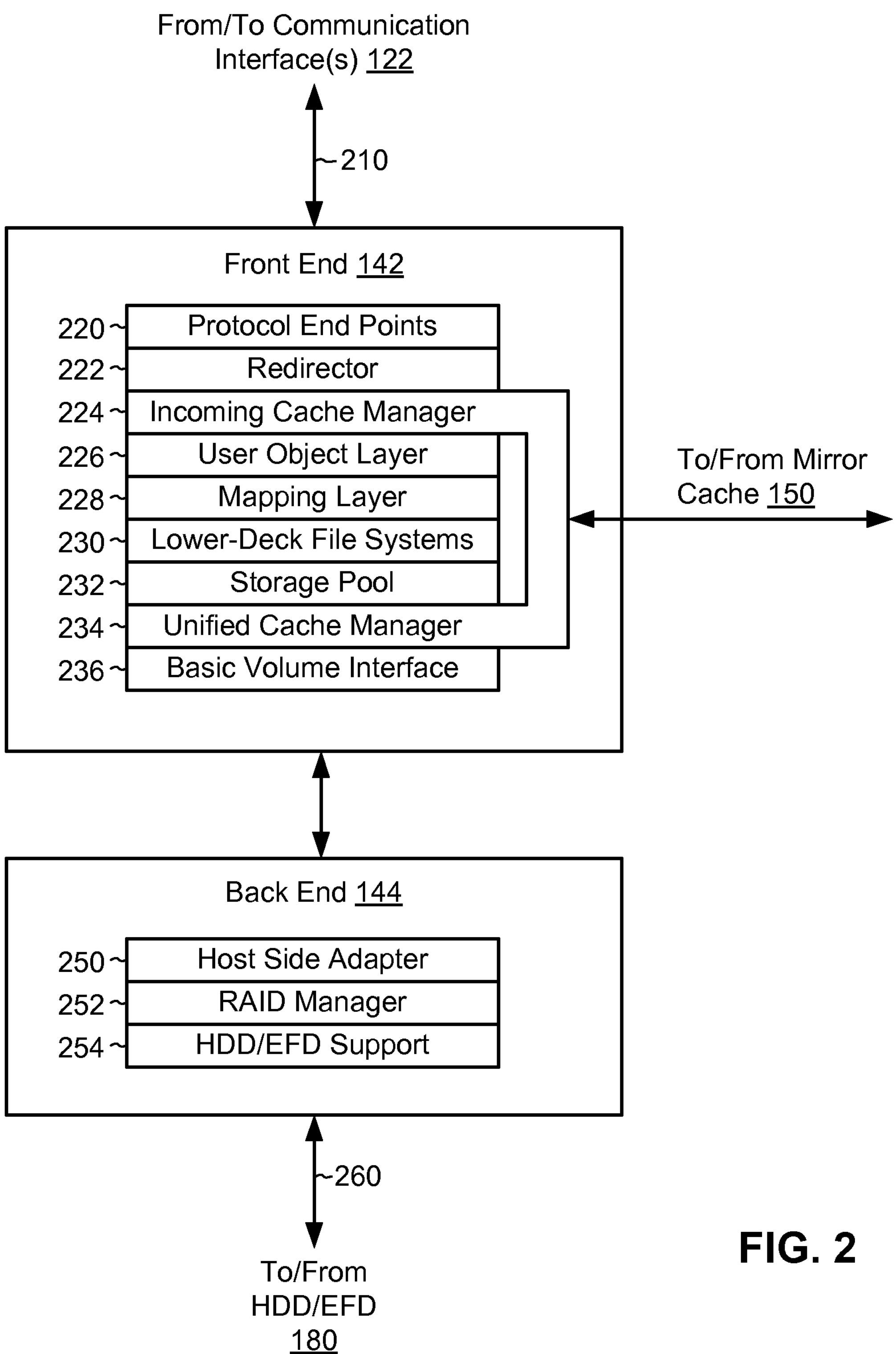

From/To Communication
Interface(s) 122
210
Front End 142
220
Protocol End Points
222
Redirector
224
Incoming Cache Manager
226
User Object Layer
228
Mapping Layer
230
Lower-Deck File Systems
232
Storage Pool
234
Unified Cache Manager
236
Basic Volume Interface
To/From Mirror
Cache 150
Back End 144
250
Host Side Adapter
252
RAID Manager
254
HDD/EFD Support
260
To/From
HDD/EFD
180

FIG. 2

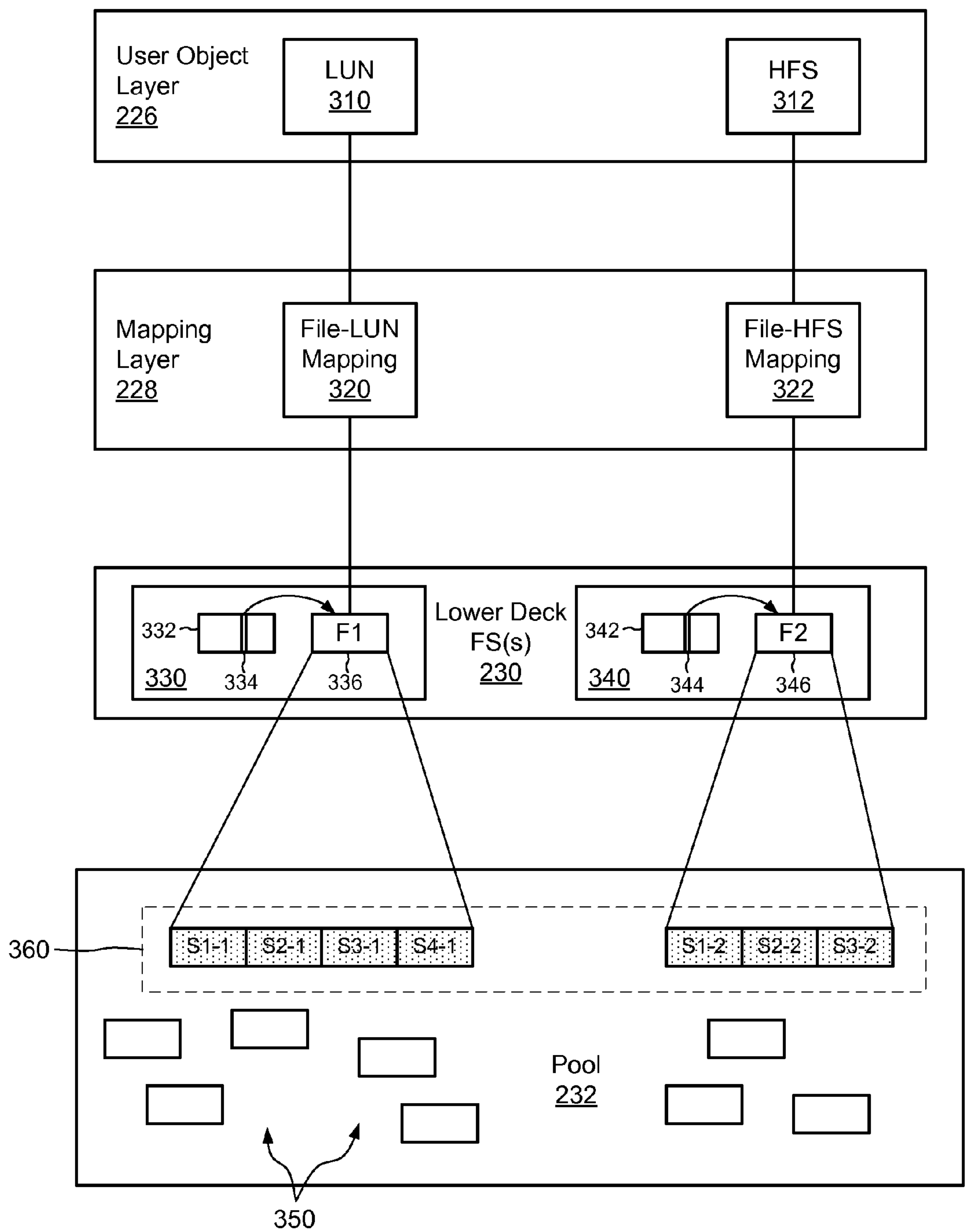

User Object Layer 226
LUN 310
HFS 312
Mapping Layer 228
File-LUN Mapping 320
File-HFS Mapping 322
332
334
F1
336
330
Lower Deck FS(s) 230
342
344
F2
346
340
360
S1-1
S2-1
S3-1
S4-1
S1-2
S2-2
S3-2
Pool 232
350

FIG. 3

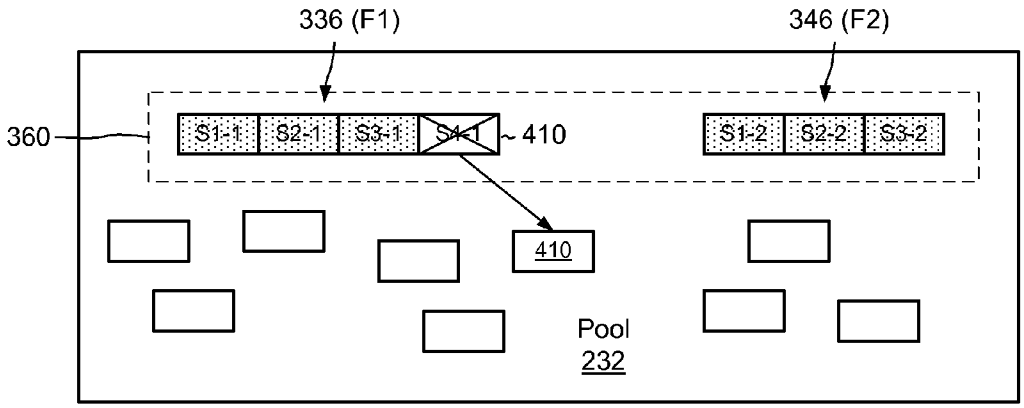


FIG. 4A

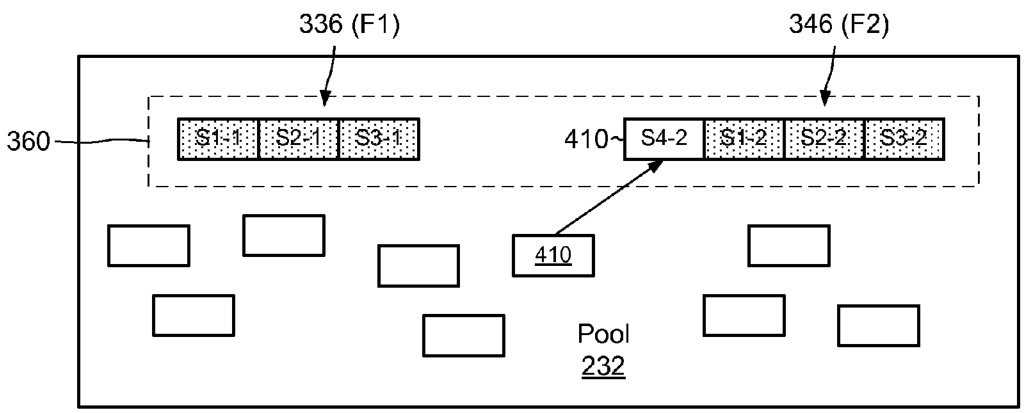


FIG. 4B

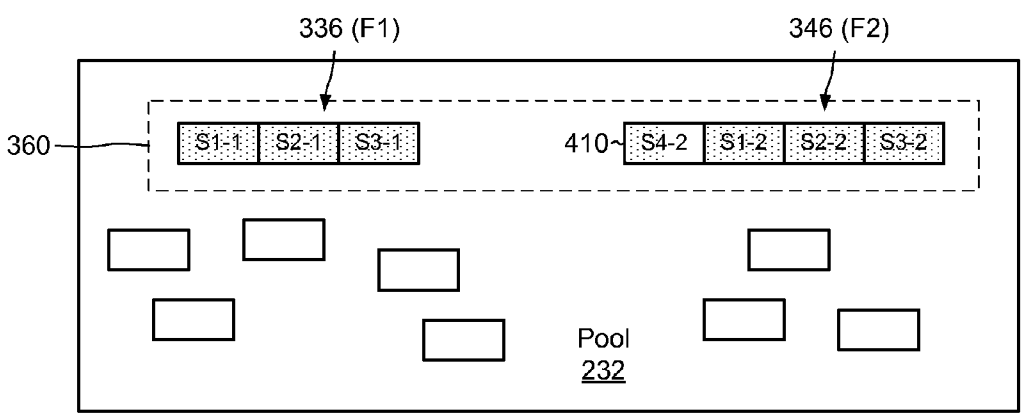


FIG. 4C

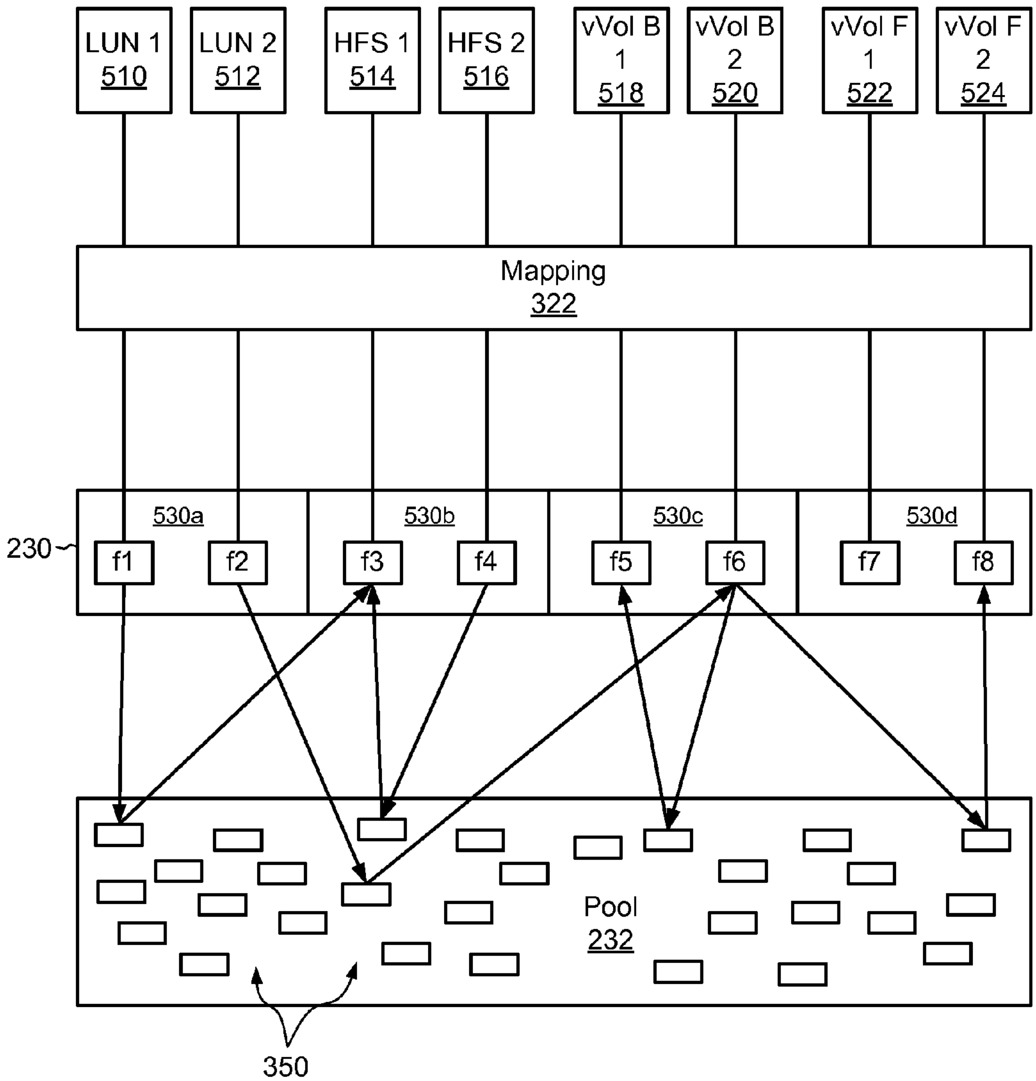

LUN 1
510
LUN 2
512
HFS 1
514
HFS 2
516
vVol B 1
518
vVol B 2
520
vVol F 1
522
vVol F 2
524
Mapping
322
230
530a
530b
530c
530d
f1
f2
f3
f4
f5
f6
f7
f8
Pool
232
350

FIG. 5

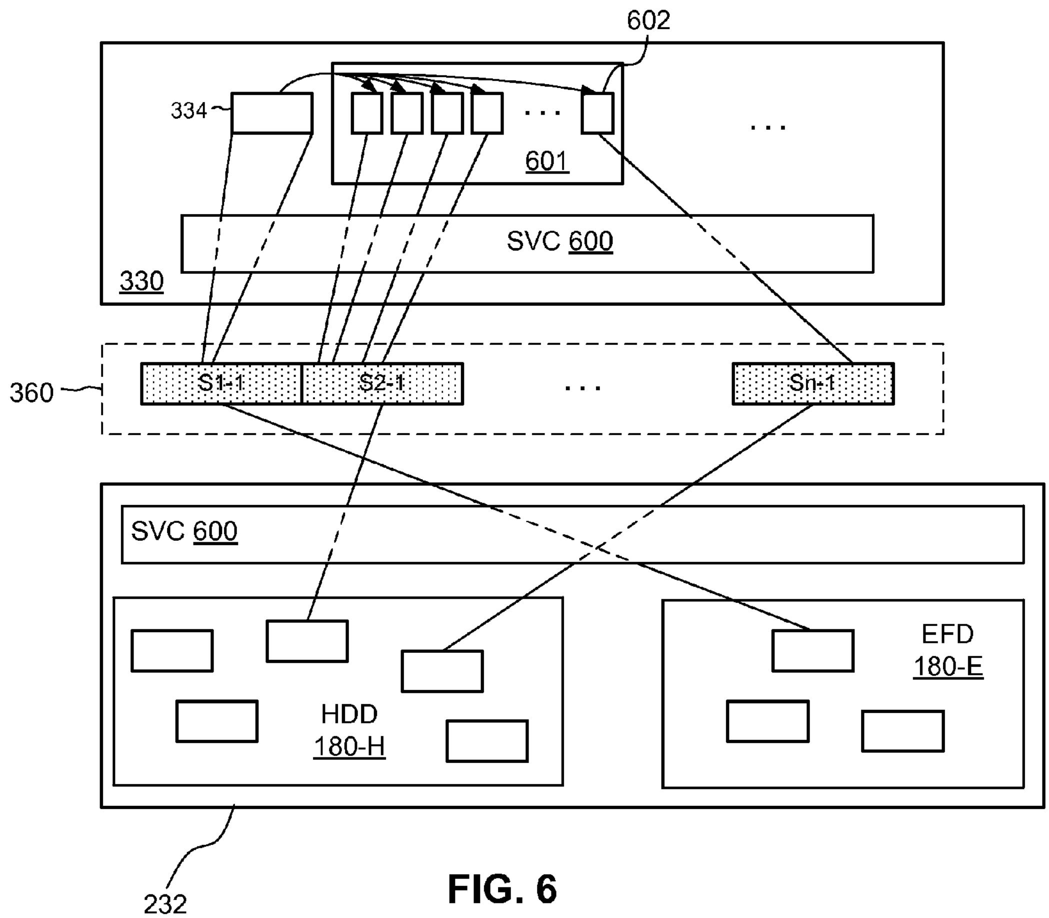

602
334
601
SVC 600
330
360
S1-1
S2-1
Sn-1
SVC 600
HDD
180-H
EFD
180-E
232

FIG. 6

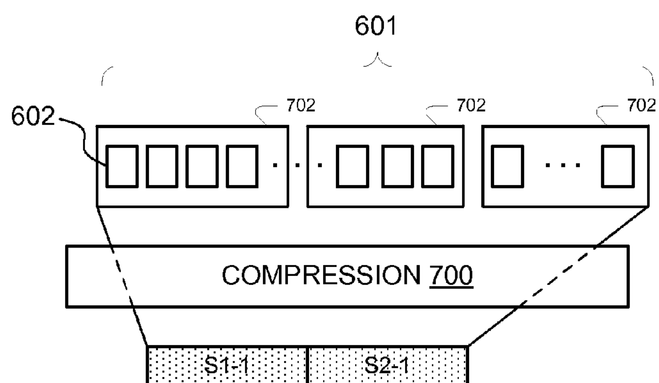

601
602
702
702
702
COMPRESSION 700
S1-1
S2-1

FIG. 7

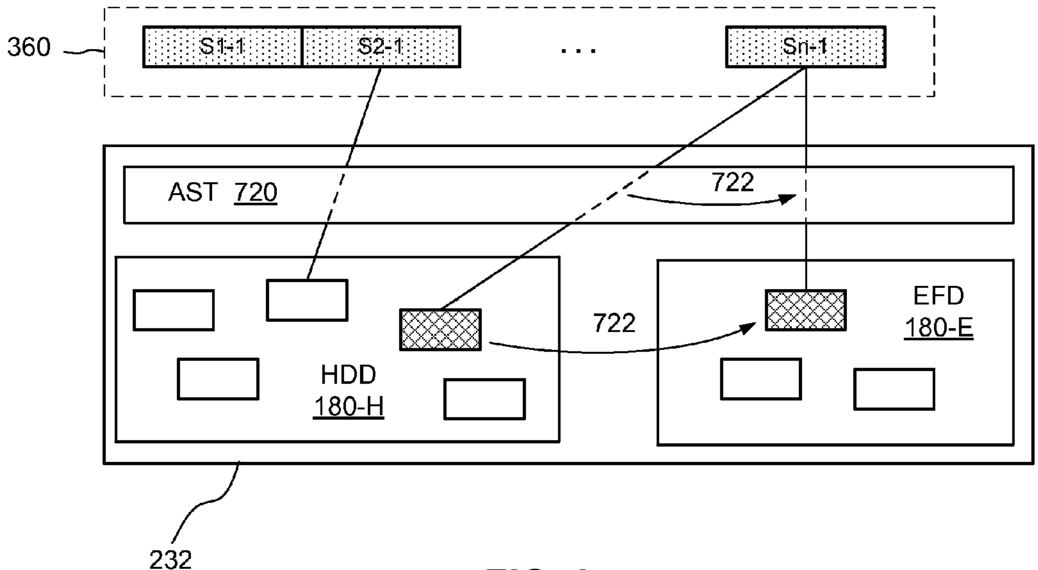

360
S1-1
S2-1
. . .
Sn-1
AST 720
722
HDD
180-H
722
EFD
180-E
232

FIG. 8

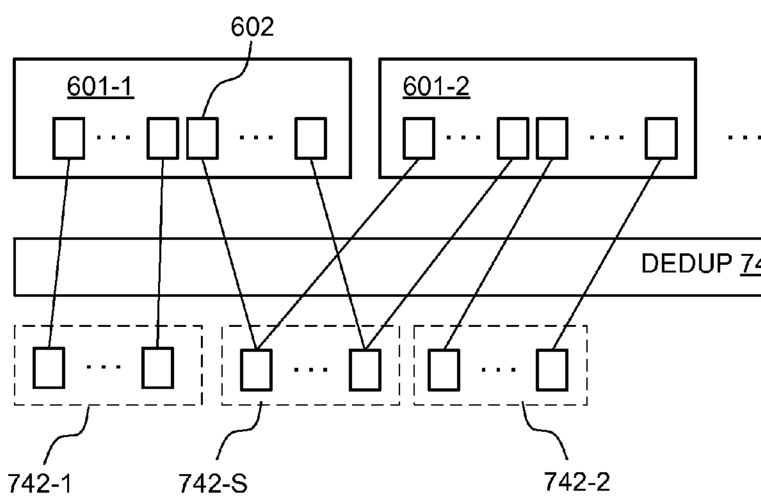

602
601-1
601-2
DEDUP 740
742-1
742-S
742-2

FIG. 9

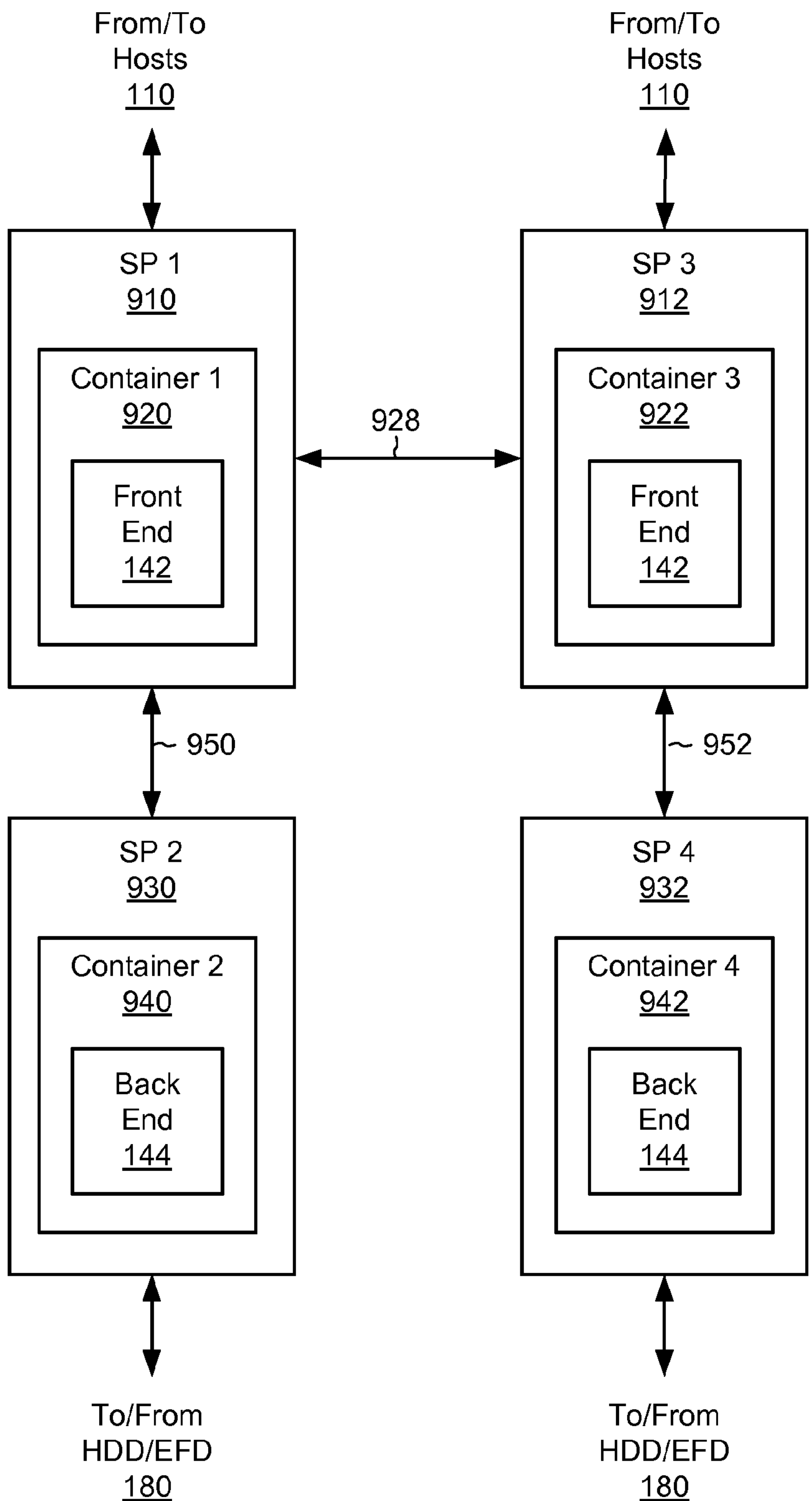

From/To
Hosts
110
From/To
Hosts
110
SP 1
910
Container 1
920
Front
End
142
928
SP 3
912
Container 3
922
Front
End
142
950
952
SP 2
930
Container 2
940
Back
End
144
SP 4
932
Container 4
942
Back
End
144
To/From
HDD/EFD
180
To/From
HDD/EFD
180

FIG. 10

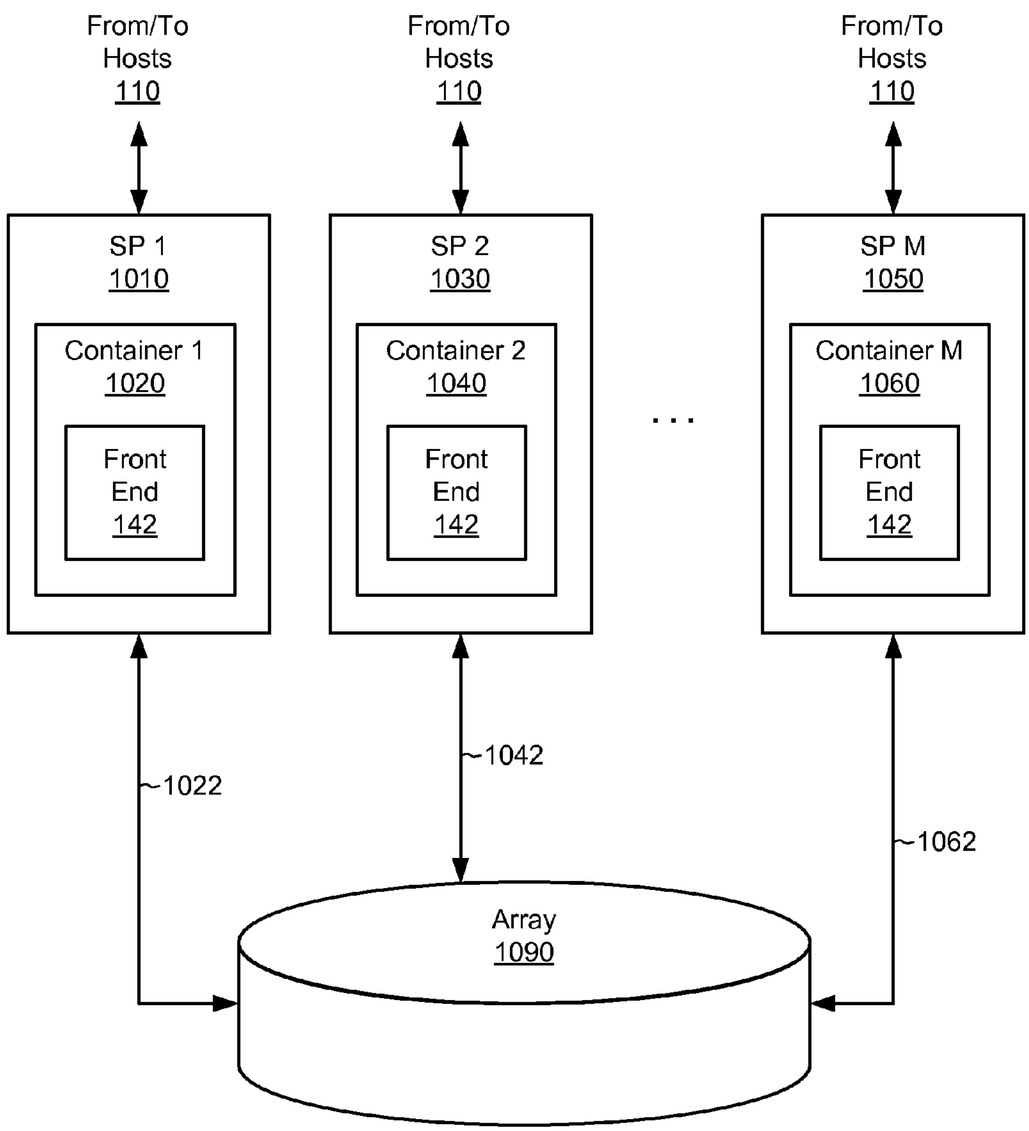

From/To
Hosts
110
From/To
Hosts
110
From/To
Hosts
110
SP 1
1010
Container 1
1020
Front
End
142
SP 2
1030
Container 2
1040
Front
End
142
SP M
1050
Container M
1060
Front
End
142
. . .
1022
1042
1062
Array
1090

FIG. 11

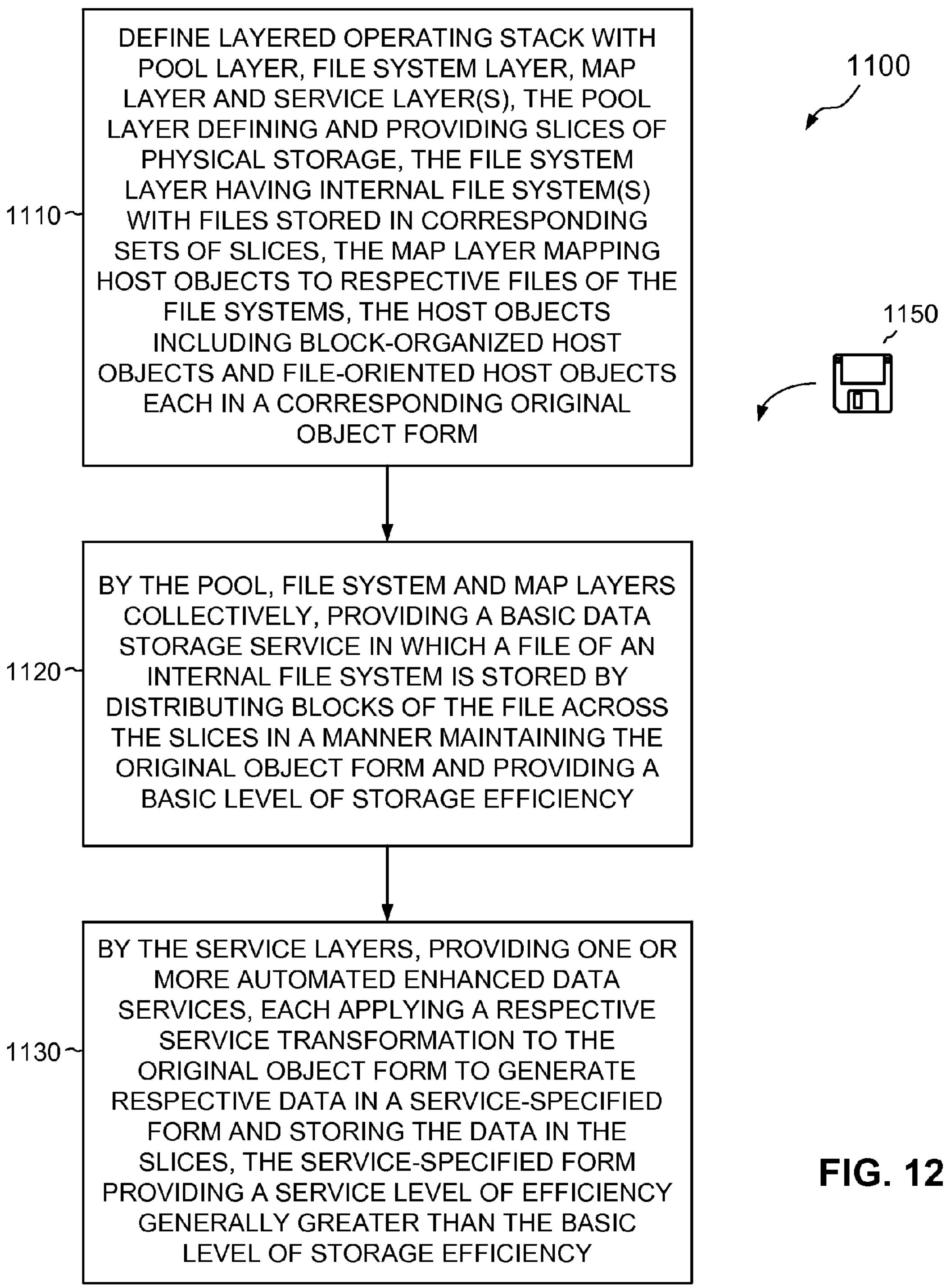

1100
1110
DEFINE LAYERED OPERATING STACK WITH POOL LAYER, FILE SYSTEM LAYER, MAP LAYER AND SERVICE LAYER(S), THE POOL LAYER DEFINING AND PROVIDING SLICES OF PHYSICAL STORAGE, THE FILE SYSTEM LAYER HAVING INTERNAL FILE SYSTEM(S) WITH FILES STORED IN CORRESPONDING SETS OF SLICES, THE MAP LAYER MAPPING HOST OBJECTS TO RESPECTIVE FILES OF THE FILE SYSTEMS, THE HOST OBJECTS INCLUDING BLOCK-ORGANIZED HOST OBJECTS AND FILE-ORIENTED HOST OBJECTS EACH IN A CORRESPONDING ORIGINAL OBJECT FORM
1150
1120
BY THE POOL, FILE SYSTEM AND MAP LAYERS COLLECTIVELY, PROVIDING A BASIC DATA STORAGE SERVICE IN WHICH A FILE OF AN INTERNAL FILE SYSTEM IS STORED BY DISTRIBUTING BLOCKS OF THE FILE ACROSS THE SLICES IN A MANNER MAINTAINING THE ORIGINAL OBJECT FORM AND PROVIDING A BASIC LEVEL OF STORAGE EFFICIENCY
1130
BY THE SERVICE LAYERS, PROVIDING ONE OR MORE AUTOMATED ENHANCED DATA SERVICES, EACH APPLYING A RESPECTIVE SERVICE TRANSFORMATION TO THE ORIGINAL OBJECT FORM TO GENERATE RESPECTIVE DATA IN A SERVICE-SPECIFIED FORM AND STORING THE DATA IN THE SLICES, THE SERVICE-SPECIFIED FORM PROVIDING A SERVICE LEVEL OF EFFICIENCY GENERALLY GREATER THAN THE BASIC LEVEL OF STORAGE EFFICIENCY

FIG. 12

UNIFIED DATA SERVICES FOR BLOCK AND FILE OBJECTS

BACKGROUND

Block-based data storage systems conventionally include programming and hardware structures to provide block-based access to storage volumes. Such systems typically support Fibre Channel, iSCSI (Internet Small Computer System Interface), and/or other block-based protocols. With any of these block-based protocols, a data storage system may receive IO (input/output) requests from "hosts," i.e., computing devices accessing the data storage system, where the IO requests (also called "host IOs") specify locations to be read from or written to in the form of LUN identifiers (logical unit number, or volume) and particular offset ranges relative to the LUNs. For responding to IOs that specify read requests, the data storage system typically maps the specified LUNs and offsets to particular locations on disk drives or electronic flash drives, reads the data stored at the mapped locations, and returns the data to the hosts. For responding to IOs that specify write requests, the data storage system performs similar mappings, but writes the data to the designated locations. The IO requests may return results indicating whether the write requests succeeded or failed. An example of a block-based data storage system is the CLARiiON® system from EMC Corporation of Hopkinton, Mass.

File-based data storage systems are also known in the art. These systems include programming and hardware structures to provide file-based access to file systems. File-based data storage systems are sometimes referred to as NAS (Network Attached Storage) systems. Such systems typically support NFS (Network File System), CIFS (Common Internet File System), SMB (Server Message Block), and/or other file-based protocols. With file-based protocols, hosts can issue read and write IO requests by specifying particular file systems, paths, and file names. Internally to the data storage system, file system directories map the files specified by the host IOs to particular sets of blocks on internal volumes, which themselves are derived from disk drives or electronic flash drives. The data storage system accesses the mapped locations and performs the requested reads or writes. An example of a file-based data storage system is the Celerra® system from EMC Corporation of Hopkinton, Mass.

SUMMARY

The designs of block-based and file-based data storage systems often follow parallel paths. Indeed, it has been recognized that many of the features provided by block-based storage, such as replication, snaps, de-duplication, migration, failover, and non-disruptive upgrade, are similar to features provided for file-based data storage systems. Because of the different ways that block-based systems and file-based systems are typically constructed, however, it can be difficult to transfer advances in features for block-based systems to file-based systems, and vice-versa.

For user convenience, block-based and file-based storage systems are sometimes co-located, essentially side-by-side, to allow processing of both block-based and file-based host IOs in a single combined system. Such combined systems are often more difficult to support and maintain, however, than block-based or file-based systems individually. In addition, such systems tend to produce "stranded storage," i.e., storage that has been freed but cannot be reused because only an object of the same type (block-based or file-based) can reuse the storage but no current demand for storage from an object of the same type is pending. Such stranded storage can accumulate in these combined systems, allowing valuable storage resources to go unutilized.

In contrast with the separate block-based and file-based designs of conventional systems, an improved technique combines both block-based and file-based functionality in a unified data path architecture. The improved technique brings together IO processing of block-based storage systems and file-based storage systems by expressing both block-based objects and file-based objects in the form of files. These files are parts of an underlying, internal set of file systems, which is stored on a set of storage units served by a storage pool. Because both block-based objects and file-based objects are expressed as files, a common set of services can be applied across block-based and file-based objects for numerous operations, such as replication, snaps, de-duplication, migration, failover, non-disruptive upgrade, and/or many other services, as these services are performed similarly for both block and file objects on the same underlying type of object—a file.

In an example, the improved technique provides one or more enhanced data services that can readily support either block-based or file-based objects. As block-based objects (e.g., LUNs, block-based vVols, and so forth) and file-based objects (e.g., file systems, file-based vVols, VMDKs, VHDs, and so forth) are expressed as underlying files, the services can be applied to the underlying files whether they represent block-based objects or file-based objects.

In accordance with improvements hereof, certain embodiments are directed to a method of providing data storage services including enhanced data services to host computers using physical storage of a storage system. A layered operating stack is defined that includes a pool layer, a file system layer, a map layer and one or more service layers, where the pool layer defines and provides slices of the physical storage for storing host data, the file system layer has one or more internal file systems with respective files stored in corresponding sets of slices, and the map layer maps host objects to respective files of the file systems. The host objects include block-organized host objects and file-oriented host objects (such as mentioned above) each in a corresponding original object form. The pool, file system and map layers collectively provide a basic data storage service in which a file of an internal file system is stored by distributing blocks of the file across the slices in a manner maintaining the original object form and providing a basic level of storage efficiency. The service layers provide one or more automated enhanced data services, each applying a respective service transformation to the original object form to generate respective data in a service-specified form and storing the data in the slices, where the service-specified form provides a service level of efficiency generally greater than the basic level of storage efficiency. Example services include compression, deduplication and automated storage tiering (AST), each employing respective service forms and methods to achieve respective increases in storage efficiency and/or performance.

Other embodiments are directed to computerized apparatus and computer program products. Some embodiments involve activity that is performed at a single location, while other embodiments involve activity that is distributed over a computerized environment (e.g., over a network).

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

The foregoing and other features and advantages will be apparent from the following description of particular embodiments of the invention, as illustrated in the accompanying drawings, in which like reference characters refer to the same parts throughout the different views. In the accompanying drawings,

FIG. **1** is a block diagram showing a data storage apparatus in an example environment wherein improved techniques hereof may be practiced;

FIG. **2** is a block diagram showing particular example features of a storage processor of FIG. **1**, including features of a front end and a back end of an IO stack;

FIG. **3** is a block diagram showing example features of the front end of FIG. **2** in additional detail, including lower-deck file systems built upon storage units (e.g., slices) from a storage pool;

FIGS. **4**A-**4**C are a series of block diagrams showing an example way in which a slice used to store a first file representing a LUN is reallocated for use by a second file representing a host file system;

FIG. **5** is a block diagram showing an example manner in which storage slices from the storage pool can be reused by different files of the lower-deck file systems;

FIG. **6** is a schematic diagram of a portion of the IO stack showing service levels;

FIGS. **7**-**9** are schematic diagrams illustrating a compression service, an automated storage tiering service, and a data deduplication service respectively;

FIG. **10** is a block diagram showing an example arrangement involving three storage processors in a modular arrangement, where two storage processors are configured to run front ends and one storage processor is configured to run a back end;

FIG. **11** is a block diagram that shows an example arrangement in which multiple storage processors run respective front ends and are connected in a gateway configuration to a data storage array; and

FIG. **12** is a flowchart showing an example process for managing host data of a set of hosts in the data storage apparatus of FIG. **1**.

DETAILED DESCRIPTION OF THE INVENTION

Embodiments of the invention will now be described. It is understood that such embodiments are provided by way of example to illustrate various features and principles of the invention, and that the invention hereof is broader than the specific example embodiments disclosed.

An improved technique for data processing in a data storage system combines both block-based and file-based functionality in a unified data path architecture. The improved technique simplifies design and maintenance and allows a common set of functions to be applied to both block-based and file-based objects. In particular, enhanced data services are provided across both types of object using one set of common mechanisms.

FIG. **1** shows an example environment **100** in which embodiments of the improved technique hereof can be practiced. Here, multiple host computing devices ("hosts"), shown as devices **110**(**1**) through **110**(N), access a data storage apparatus **116** over a network **114**. The data storage apparatus **116** includes a storage processor, or "SP," **120** and storage **180**. The storage **180** is provided, for example, in the form of hard disk drives (HDD) and/or electronic flash drives (EFD). Although not shown in FIG. **1**, the data storage apparatus **116** may include multiple SPs like the SP **120**. For instance, multiple SPs may be provided as circuit board assemblies, or "blades," which plug into a chassis that encloses and cools the SPs. The chassis has a backplane for interconnecting the SPs, and additional connections may be made among SPs using cables. It is understood, however, that no particular hardware configuration is required, as any number of SPs (including a single one) can be provided and the SP **120** can be any type of computing device capable of processing host IOs.

The network **114** can be any type of network or combination of networks, such as a storage area network (SAN), local area network (LAN), wide area network (WAN), the Internet, and/or some other type of network, for example. In an example, the hosts **110**(**1**-N) connect to the SP **120** using various technologies. For example, the host **110**(**1**) can connect to the SP **120** using Fibre Channel (e.g., through a SAN). The hosts **110**(**2**-N) can connect to the SP **120** using TCP/IP, to support, for example, iSCSI, NFS, SMB 3.0, and CIFS. Any number of hosts **110**(**1**-N) may be provided, using any of the above protocols, some subset thereof, or other protocols besides those shown. As is known, Fibre Channel and iSCSI are block-based protocols, whereas NFS, SMB 3.0, and CIFS are file-based protocols. The SP **120** is configured to receive IO requests **112**(**1**-N) according to both block-based and file-based protocols and to respond to such IO requests **112**(**1**-N) by reading or writing the storage **180**.

The SP **120** is seen to include one or more communication interfaces **122**, a set of processors **124**, and memory **130**. The communication interfaces **122** include, for example, adapters, such as SCSI target adapters and network interface adapters, for converting electronic and/or optical signals received from the network **114** to electronic form for use by the SP **120**. The set of processors **124** includes one or more processing chips and/or assemblies. In a particular example, the set of processors **124** includes numerous multi-core CPUs. The memory **130** includes both volatile memory (e.g., RAM), and non-volatile memory, such as one or more ROMs, disk drives, solid state drives (SSDs), and the like. The set of processors **124** and the memory **130** together form control circuitry, which is constructed and arranged to carry out various methods and functions as described herein. Also, the memory **130** includes a variety of software constructs realized in the form of executable instructions. When the executable instructions are run by the set of processors **124**, the set of processors **124** are caused to carry out the operations of the software constructs. Although certain software constructs are specifically shown and described, it is understood that the memory **130** typically includes many other software constructs, which are not shown, such as various applications, processes, and daemons.

As shown, the memory **130** includes an operating system **134**, such as Unix, Linux, or Windows™, for example. The operating system **134** includes a kernel **136**. The memory **130** further includes a container **132**. In an example, the container **132** is a software process that provides an isolated userspace execution context within the operating system **134**. In various examples, the memory **130** may include multiple containers like the container **132**, with each container providing its own isolated userspace instance. Although containers provide isolated environments that do not directly interact (and thus promote fault containment), different containers can run on the same kernel **136** and can communicate with one another using inter-process communication (IPC) mediated by the kernel **136**. Containers are well-known features of Unix, Linux, and other operating systems.

In the example of FIG. **1**, only a single container **132** is shown. Running within the container **132** is an IO stack **140**, a mirror cache **150**, and a replicator **160**. The IO stack **140** provides an execution path for host IOs (e.g., **112**(**1**-N)) and includes a front end **142** and a back end **144**. The mirror cache **150** stores data for incoming writes and mirrors the data to cache on another SP. The replicator **160** makes local and/or remote copies of data for incoming writes. As the IO stack **140**, mirror cache **150**, and replicator **160** all run within the same container **132**, the IO stack **140**, mirror cache **150**, and replicator **160** can communicate with one another using APIs (application program interfaces), i.e., without the need to use IPC.

The memory **130** also stores a configuration database **170**. The configuration database **170** stores system configuration information. In other implementations, the configuration database **170** is stored elsewhere in the data storage apparatus **116**, such as on a disk drive separate from the SP **120** but accessible to the SP **120**, e.g., over a backplane or network.

In operation, the hosts **110**(**1**-N) issue IO requests **112**(**1**-N) to the data storage apparatus **116**. The IO requests **112**(**1**-N) may include both block-based requests and file-based requests. The SP **120** receives the IO requests **112**(**1**-N) at the communication interfaces **122** and passes the IO requests to the IO stack **140** for further processing. At the front end **142**, processing may include caching data provided with any write IO requests to the mirror cache **150**, which may in turn cache the data to another SP. Also within the front end **142**, mapping operations map LUNs and host file systems to underlying files stored in a set of internal file systems of the front end **142**. Host IO requests received for reading and writing both LUNs and file systems are thus converted to reads and writes of respective files. The IO requests then propagate to the back end **144**, where commands are executed for reading and/or writing the physical storage **180**, agnostically to whether the data read and/or written is directed to a LUN or to a host file system.

Although FIG. **1** shows the front end **142** and the back end **144** together in an "integrated" form, the front end **142** and back end **144** may alternatively be provided on separate SPs. For example, the IO stack **140** may be implemented in a "modular" arrangement, with the front end **142** on one SP and the back end **144** on another SP. The IO stack **140** may further be implemented in a "gateway" arrangement, with multiple SPs running respective front ends **142** and with a back end provided within a separate storage array. The back end **144** performs processing that is similar to processing natively included in many block-based storage arrays. Multiple front ends **142** can thus connect to such arrays without the need for providing separate back ends.

FIG. **2** shows the front end **142** and back end **144** of the IO stack **140** in additional detail. Here, the front end **142** is seen to include protocol end points **220**, a redirector **222**, an incoming cache manager **224**, a user object layer **226**, a mapping layer **228**, one or more lower-deck (internal) file systems **230**, a storage pool **232**, a unified cache manager **234**, and a basic volume interface **236**. The back end **144** is seen to include a host side adapter **250**, a RAID (Redundant Array of Independent Disks) manager **252**, and hard disk drive/electronic flash drive support **254**.

Within the front end **142**, protocol end points **220** receive the host IO requests **210** from the communication interfaces **122** and perform protocol-specific processing, such as stripping off header information and identifying data payloads. Processing then continues to the redirector **222**.

The redirector **222** receives the host IOs and, under specified conditions, redirects the host IO requests to another SP. For example, the LUN specified in any block-based host IO request may be owned by a particular SP of the data storage apparatus **116**. If the SP **120** receives a host IO request that is directed to a LUN owned by another SP, the redirector **222** sends the host IO to the SP that owns the LUN, at which point processing of the host IO request by the SP **120** ceases. However, if the redirector **222** detects that the LUN specified in a block-based host IO request is owned by the SP **120**, the redirector allows the host IO request to continue to propagate through the front end **142**. The redirector **222** performs no operation for file-based host IO requests. For host IO requests that are not redirected, processing continues to the incoming cache manager **224**.

The incoming cache manager **224** provides low-latency responses to incoming host IO write requests. When a write IO request is received, the incoming cache manager **224** caches the data specified by the write request in the mirror cache **150**. Operating in conjunction with the unified system cache **234**, the incoming cache manager **224** directs the contents of the mirror cache **150** to be copied over a high-speed interconnect (e.g., a high-speed cable or bus) to a cache of a second SP of the data storage apparatus, where a duplicate copy of the data is stored. The data specified by the host write IO request are thus stored in two independent locations and are deemed to be persisted. Upon confirmation that the data have been successfully written to both the mirror cache **150** and the cache of the other SP, the incoming cache manager **224** acknowledges the write back to the originating host (i.e., the host of **110**(**1**-N) that sent the write host IO). Using this arrangement, write requests are acknowledged quickly, without the need to wait until the requests propagate to the actual storage **180** or even to the unified cache manager **234**, thereby providing a low level of latency in responding to write IOs. The data stored in the mirror cache **150** may eventually be destaged to the storage **180** (e.g., to the set of slices that store the LUN or file system being written to), but such destaging may be conducted when convenient and out of band with the processing of host IOs. Processing continues to the incoming user object layer **226**.

The user object layer **226** presents underlying files representing LUNs and underlying files representing host file systems in a form recognized by the hosts (i.e., as LUNs and host file systems). For example, the user object layer **226** presents data stored in underlying files for block-based data as LUNs. The user object layer **226** also presents data stored in underlying files for file-based data as host file systems. In an example, the user object layer **226** includes an upper-deck file system for each host file system stored in a file of the lower-deck file system(s) **230** (described below). Each upper-deck file system presents files and directories of a host file system to the hosts **110**(**1**-N), even though the host file system is represented internally as a file.

The mapping layer **228** maps host objects as presented in the user object layer **226** to corresponding underlying files stored in one or more lower-deck file systems **230**. For LUNs, the mapping layer **228** converts a LUN identifier and offset range to a particular file in a lower-deck file system **230** and to a particular offset range within that file. Any set of blocks of a LUN identified in a host IO request are thus mapped to a set of blocks in the underlying file that represents the LUN. Similarly, for host file systems, the mapping layer **228** converts a given file or directory represented in an upper-deck file system of the user object layer **226** to a particular file in a lower-deck file system **230** and to a particular location within the file.

The lower-deck file system layer **230** represents LUNs and host file systems in the form of files. Any number of lower-deck file systems **230** may be provided. In one arrangement, a single lower-deck file system **230** may be provided to include any number of LUNs and/or host file systems, as well as their snaps (i.e., point-in-time copies). In another arrangement, a different lower-deck file system is provided for each primary object to be stored, i.e., for each LUN and for each host file system. The lower-deck file system for any primary object may include a file storing the object itself, as well as files storing any snaps of the object. Each lower-deck file system **230** has an inode table, which provides a unique inode for each file stored in the lower-deck file system **230**. The inode table of each lower-deck file system stores properties of each file in the respective lower-deck file system, such as ownership and block locations at which the file's data are stored. Lower-deck file systems are built upon storage elements managed by a storage pool **232**.

The storage pool **232** organizes elements of the storage **180** in the form of slices. A "slice" is an increment of storage space, such as 256 MB in size, which is drawn from the storage **180**. The pool **232** may allocate slices to lower-deck file systems **230** for use in storing their files. The pool **232** may also deallocate slices from lower-deck file systems **230** if the storage provided by the slices is no longer required. In an example, the storage pool **232** creates slices by accessing RAID groups formed from the storage **180**, dividing the RAID groups into FLUs (Flare LUNs), and further dividing the FLU's into slices.

The unified cache manager **234** provides caching services for data stored in the lower-deck file systems **230**. In some examples, the unified cache manager **234** directs data specified by host writes to local RAM or flash memory and thus avoids the need to access the storage **180**, which is typically more remote than the local RAM or flash memory and takes more time to access. In some examples, the unified cache manager **234** also directs data returned in response to read IO requests to be stored in local RAM or flash memory for fast access in the event that subsequent host IO requests require the same data. In some examples, the local RAM or flash memory may store the only valid copy of host data, with writes to the storage **180** being deferred and, in cases where host data needs to be stored only transiently, avoided altogether.

The basic volume interface **236** is arranged to send host IOs to the back end **144** when the back end **144** is provided on another SP of the data storage apparatus **116** or when the back end **144** is provided on a separate array. In an example, the basic volume interface **236** converts host IOs propagating out of the front end **142** to a block-based protocol, such as Fibre Channel. After being processed by the basic volume interface **236**, processing continues to the back end **144**.

Within the back end **144**, the host side adapter **250** receives the host IO and extracts the host IO content. In some implementations, such as the "integrated" arrangement shown in FIG. **1**, the basic volume interface **236** and host side adapter **250** may be omitted or may be made to perform no operation.

The RAID manager **252** accesses the particular slice or slices being written or read using RAID protocols. In some examples, the RAID manager **252** also performs out-of-band operations of maintaining RAID groups, such as swapping out failing disk elements and applying erasure coding to restore required redundancy.

The hard disk drive/electronic flash drive support **254** includes drivers that perform the actual reading from or writing to the storage **180**.

Although the above-described components of the IO stack **140** are presented in a particular order, this order can be varied. For example, the incoming cache manager **224** can be located above the redirector **222**. Also, multiple cache managers can be provided at different locations within the IO stack **140**.

FIG. **3** shows portions of the front end **142** in additional detail. Here, the user object layer **226** includes a representation of a LUN **310** and of an HFS (host file system) **312**, and the mapping layer **228** includes a file-to-LUN mapping **320** and a file-to-HFS mapping **322**. The file-to-LUN mapping **320** maps the LUN **310** to a first file F**1** (**336**), and the file-to-HFS mapping **322** maps the HFS **312** to a second file F**2** (**346**). Through the file-to-LUN mapping **320**, any set of blocks identified in the LUN **310** by a host IO is mapped to a corresponding set of blocks within the first file **336**. Similarly, through the file-to-HFS mapping **322**, any file or directory of the HFS **312** is mapped to a corresponding set of blocks within the second file **346**.

The first file **336** and the second file **346** are included within the lower-deck file systems **230**. In this example, a first lower-deck file system **330** includes the first file **336** and a second lower-deck file system **340** includes the second file **346**. Each of the lower-deck file systems **330** and **340** includes an inode table, **332** and **342**, respectively. The inode tables **332** and **342** provide information about files in respective lower-deck file systems in the form of inodes. For example, the inode table **332** of the first lower-deck file system **330** includes an inode **334**, which provides file-specific information about the first file **336**. Similarly, the inode table **342** of the second lower-deck file system **340** includes an inode **344**, which provides file-specific information about the second file **346**. The information stored in each inode includes location information (e.g., block locations) where the respective file is stored, and may thus be accessed as metadata to identify the locations of the files **336** and **346**.

Although a single file is shown for each of the lower-deck file systems **330** and **340**, it is understood that each of the lower-deck file systems **330** and **340** may include any number of files, each with its own entry in the respective inode table. In one example, each lower-deck file system stores not only the file F**1** or F**2** for the LUN **310** or HFS **312**, but also snaps of those objects. For instance, the first lower-deck file system **330** stores the first file **336** along with a different file for every snap of the LUN **310**. Similarly, the second lower-deck file system **340** stores the second file **346** along with a different file for every snap of the HFS **312**.

As shown, a set of slices **360** is allocated by the storage pool **232** for storing the first file **336** and the second file **346**. In the example show, slices S**1-1** through S**4-1** are used for storing the first file **336**, and slices S**1-2** through S**3-2** are used for storing the second file **346**. The data that make up the LUN **310** are thus stored in the slices S**1-1** through S**4-1**, whereas the data that make up the HFS **312** are stored in the slices S**1-2** through S**3-2**. In an example, the storage pool **232** allocates slices **350** to the set of file systems **230** in an on-demand manner, e.g., as the first file **236** and the second file **246** require additional storage. The storage pool **232** can also deallocate slices from the set of file systems **230** when all the currently allocated slices are no longer required.

In some examples, each of the lower-deck file systems **330** and **340** is associated with a respective volume, such as a sparse LUN. Sparse LUNs provide an additional layer of mapping between the lower-deck file systems **230** and the pool **232** and allow the lower-deck file systems to operate as file systems normally do, by accessing underlying volumes. Additional details about sparse LUNs and their relation to lower-deck file systems may be found in U.S. Pat. No. 7,631,155, which is hereby incorporated by reference in its entirety. The incorporated patent uses the term "container file systems" to refer to constructs similar to the lower-deck file systems disclosed herein.

FIGS. **4A-4C** show a sequence of events for reusing a slice **410** that once stored portions of the first file **336** for storing portions of the second file **346** when the slice **410** is no longer required by the first file **336**. In FIG. **4A**, it is shown that slice

S4-1 (also labeled **410**), which previously stored data for the first file **336**, has become empty. This may occur, for example, when data is deleted from the LUN **310**. In response to the slice S4-1 (**410**) becoming empty, the storage pool **232** deallocates the slice **410** from the set of file systems **230** and makes the slice **410** available.

In FIG. **4**B, the free slice **410** is reallocated to the set of file systems **230** for use by the second file **346**. Thus, the slice **410** becomes a newly added slice S**4-2**. In an example, the pool **232** reallocates the slice **410** to the set of file systems in response to the second file **346** requiring additional storage. This may occur, for example, in response to the HFS **312** growing to accommodate additional, or larger, files.

In FIG. **4**C, with the first file **346** still storing data for the LUN **310**, the slice **410** has become part of the second file **346** (as slice S4-2) and additional data for the second file **346** are stored on the newly acquired slice.

In the manner shown, a slice first used by the LUN **310** is reused by the HFS **312**. Thus, storage space originally used for storing block-based data is reused for storing file-based data. Although FIGS. **4**A-**4**C show block-based storage being reused for file-based storage, it is evident that file-based storage can also be reused for block-based storage. For example, the slice **410** can be released from the second file **346** and reused by the first file **336**. Thus, inefficiencies of stranded storage are significantly reduced or eliminated.

FIG. **5** shows a flexible manner in which files of lower-deck file systems can store a variety of host objects and how slices can be readily reused across different files. Here, files f**1** and f**2** within a lower-deck file system **530***a* store file representations of LUNs **510** and **512**. Also, files f**3** and f**4** within a lower-deck file system **530***b* store file representations of host file systems **514** and **516**. Additional host objects are stored, including block-based vVols **518** and **520** in files f**5** and f**6** (in a lower-deck file system **530***c*), and file-based vVols **522** and **524** in files f**7** and f**8** (in a lower-deck file system **530***d*). As is known, vVols are virtual storage volumes that are associated with particular virtual machines. In an example, any of the hosts **110**(**1**-N) may run a virtual machine, which references a vVol stored on the data storage apparatus **116**.

As illustrated with the arrows extending between the files f**1** through f**8** and slices **350** in the pool **232**, slices used for any of the files f**1** through f**8** can be deallocated when they are no longer needed and reallocated for use with other files as those files require additional storage. As all host objects (e.g., LUNs, host file systems, block-based vVols, or file-based vVols) are represented as files, slices may be readily exchanged among them. Stranded storage is thus avoided for all of these host object types.

FIG. **6** shows a further aspect of the storage system, specifically one or more service layers **600** for providing enhanced data services in connection with the storage of host objects. These include block-based host objects and file-based host objects, such as the LUNs **310** and host file systems **312** respectively of FIG. **3**. As described above, both of these types of host objects (block-based and file-based) are stored in files (e.g., files **336**, **346** in FIG. **3**; shown as **601** in FIG. **6**) of lower-deck file systems **330**. In FIG. **6** the service layers **600** are shown as residing in a file system **330** and/or as part of the pool **232**. In general, enhanced data services as described herein are provided at or below the level of the lower-deck file systems **330**, thereby supporting both block-based and file-based services provided to the hosts **110** by operating on the same file abstraction utilized by both. Enhanced data services provide transformations (static or dynamic) of the original object form of the host object to a service-specified form used at lower levels to achieve the desired performance objective. Several specific examples of such services and their transformations are provided below.

FIG. **6** also shows the structure of a file **601** of a lower-deck file system **330**. The data of the file is distributed across a set of fixed-size blocks **602**. These are mapped to respective slices Sx-**1** such as shown. Also illustrated is the manner in which the slices Sx-**1** are allocated from the pool **232**. As indicated above, the pool **232** draws underlying storage from either or both HDD storage **180**-H and EFD storage **180**-E. In this simplified example a first slice S**1-1** used to store inodes **334** resides on EFD **180**-E, while the other slices reside on HDD **180**-H. The EFD **180**-E may be used for the metadata slice S**1-1** to enable higher performance of the file system **330**, due to the relatively high frequency and latency sensitivity of the accesses to the metadata slice S**1-1**.

FIG. **6** illustrates what is referred to as a "basic" level of data storage service provided by the pool layer **232**, file system layer **230** and mapping layer **228** collectively. The service is basic in the sense that it substantially mirrors the block-by-block original-object structure of the file **601** onto the slices Sx, albeit with a flexible block placement that enables the slices Sx to be used most efficiently. That is, each block **602** is mapped to and stored as a corresponding block of a slice Sx. If the file **601** contains 150 blocks **602**, then a corresponding 150 blocks of slices Sx are used. Also, basic service implies a default use of a certain type of storage **180** for the slices Sx of the file **330**, such as the relatively lower-performance HDD **180**-H rather than the EFD **180**-E. There may be a higher-level mechanism for assigning individual files **330** to EFD **180**-E rather than HDD **180**-H, but even in this case the assignment is generally static absent operator intervention.

FIGS. **7-9** show certain enhanced data services that employ the structure of FIG. **6**. In each case, the mapping of the blocks **602** of the file **601** to the storage **180** is modified from that of the basic service. FIG. **7** describes a data compression service; FIG. **8** describes an automated storage tiering (AST) service; and FIG. **9** describes a data deduplication (DEDUP) service. Again, it will be appreciated that because these services are provided at or below the lower-deck file system layer **230**, they readily support both block and file host objects (i.e., LUNs **310** and HFSs **312**) that rely on the file abstraction of the underlying physical storage.

FIG. **7** illustrates a data compression service **700**, which might be deployed in file system **330** or between the file system **330** and the pool **232**. The blocks **602** of the file **601** are shown in slice-sized sets **702**, i.e., within each set **702** is the fixed number of blocks **602** corresponding to the size of a slice Sx. In the case of 8 Kbyte blocks and 256 Mbyte slices, for example, each set **702** has 32 K blocks **602**. The compression service **700** applies a compression encoding to the sets **702** to generate a compressed representation stored on underlying slices Sx, where generally the number of slices required for the underlying storage is considerably less than the size of the file as measured in slice-sized sets **702**. In the simplified example of FIG. **7**, the data of three sets **702** are compressed into two slices S**1-1** and S**2-1** as shown. In operation, the compression service **700** also performs the inverse operation, decompression, on the slices Sx to re-generate the original sets **702** of blocks **602** according to the original object form from a host **110**.

Any of a variety of specific data compression algorithms may be used by the compression service **702**, and the specific algorithm may vary depending on more specific type information about the host object. Different types of algorithms have been developed for text and media, for example, and for media there are different types of algorithms for images, video and audio for example. The compression service **700** may provide only one type of compression, which may be applied to all or selected ones of the files **601** of a file system **330**. Alternatively, the compression service **700** may provide multiple types of compression and include a mechanism for selectively applying these to corresponding host objects as appropriate (i.e., audio compression to audio files, etc.). In this respect, the upper layers (e.g., host object layer **226**, mapping layer **228**) may provide object type information that can form metadata for files **601** of a lower-deck file system **330**, such metadata being usable by the service(s) **600** for the purpose of selecting appropriate compression for each file **601**.

FIG. **8** illustrates the automated storage tiering (AST) service **720**, which is provided at the level of the storage pool **232**. While the compression service **700** achieves enhanced data storage in form of increased storage usage efficiency (ability to store more user data for a given size or amount of underlying storage **180**), the AST service **720** provides the ability to achieve a desired balance between storage usage efficiency and performance (e.g., latency and throughput). Data is automatically and dynamically moved between storage-efficient HDD **180**-H and the higher-performance EFD **180**-E according to patterns of usage of the data, favoring the faster EFD **180**-E for more frequently accessed data and the denser HDD **180**-H for less frequently accessed data.

As shown in FIG. **8**, the AST service **720** manages the assignment of the slices Sx to the pool **232**. In the simplified example shown, slice Sn-**1** is initially provided from the HDD storage **180**-H. This may correspond, for example, to an initial assignment when the slice is created and assigned for use by the file system **601**. During operation, the AST service **720** monitors the pattern of access (reads and/or writes) of the slice Sn-**1**, and upon this pattern meeting some threshold the slice is automatically reassigned (indicated by arrows **722**) to the EFD **180**-E. It will be appreciated that this reassignment involves atomically reading the slice from the HDD **180**-H and writing it to the EFD **180**-E, along with updating any data structures or other mechanisms that reflect the location of the slice in storage **180**. There may be a similar mechanism for moving slices in the other direction, i.e., from EFD **180**-E to HDD **180**-H. Algorithms for automated storage tiering are generally known and not elaborated herein. Although in the example of FIG. **8** there are only two storage types or tiers **180**-E and **180**-H, in general there may be any number of tiers and corresponding algorithms and thresholds for automatically transferring slices among them.

FIG. **9** illustrates the deduplication service (DEDUP) **740**. Like the compression service **700**, it provides for enhanced data storage in the form of greater storage usage efficiency. In particular, in one embodiment it operates across a set of multiple files **601** of a given file system **330**. The corresponding host objects (e.g., LUNs **310** or HFSs **312**) stored in the files **601** form a "deduplication domain" in which duplicate data elements are removed and replaced with pointers to shared single instances of the data elements. In the illustrated example, the deduplication service **740** detects blocks **602** that are identical between two or more files **601**, and instead of storing each identical copy the deduplication service **740** stores only one instance and provides a pointer for each file **601** to the stored copy. This is illustrated in FIG. **9** by the mapping from the original object form of files **601-1** and **601-2** to three sets **742** of blocks: one set **742-1** unique to file **601-1**, one set **742-2** unique to file **601-2**, and a third set **742**-S that are shared between the two files **601**. It will be appreciated that the three sets **742** consume less overall storage space than the complete set of blocks **602** for both files **601-1** and **601-2**. Techniques for providing such block-based deduplication are generally known in the art and are not elaborated further herein.

Although FIG. **9** shows a deduplication domain as including multiple files **601**, in some cases it may be useful to apply deduplication even within a single file **601**. This may be the case, for example, when the single file **601** stores a host file system **312**, which in general may include large numbers of individual files with replicated contents.

In alternative embodiments, there may be multiple pools **232** in a given storage device, and each pool **232** includes a deduplication "container" providing a single deduplication domain for the pool. Within a deduplication domain many files **601** may be hosted along with respective snaps. Each of the files **601** may be hosting different object types such as LUN, vVol and host file system. Such an arrangement enables block level deduplication across all these different objects.

It should also be noted that the services of the service layers **600** are not necessarily mutually exclusive. For example, files **601** in a deduplication container may be compressed in addition to being deduplicated to further improve the storage efficiency.

FIGS. **10** and **11** show different deployments of the IO stack **140**. In FIG. **10**, a modular deployment is shown in which a first SP **910** houses a front end **142** in a first container **920** and a second SP **930** houses the back end **144** in a second container **940**. An interconnection **950** is formed between the first SP **910** and the second SP **930**. In an example, the interconnection **950** is made using Fibre Channel or some other block-based protocol. To support cache mirroring (via connection **928**), as well as other functions, a parallel arrangement may be formed with a third SP **912** housing a front end **142** in a third container **922** and a fourth SP **932** housing a back end **144** in a fourth container **942**. An interconnection **952** is formed between the third SP **912** and the fourth SP **932**. With this arrangement, performance gains can be realized over the integrated configuration of FIG. **1**, because the modular configuration dedicates the computing and memory resources of multiple SPs to handling host IOs, and because each SP is optimized for operating as a front end or as a back end but is not required to operate as both. Also, although the first SP **910**, the second SP **930**, the third SP **912**, and fourth SP **932** are physical SPs, any of the SPs housing front ends **142** (SP**1** and SP**3**) can themselves house any number of virtualized storage processors.

FIG. **11** shows a gateway arrangement, in which multiple SPs **1010**, **1030**, . . . , **1050** each house a front end **142** in respective containers **1020**, **1040**, . . . , **1060**. Interconnections **1022**, **1042**, . . . , **1062** (such as Fibre Channel) respectively connect the SPs **1010**, **1030**, . . . , **1050** to an array **1090**. The array **1090** includes its own internal back end, for responding to block-based IOs. Although three SPs are shown providing front ends **142**, it is understood that a greater or lesser number of SPs providing front ends **142** may be provided. Also, cache mirroring and other functions may be best supported by providing SPs in pairs. Thus, the number of SPs in the gateway arrangement is preferably even. Suitable examples of the array **1090** include the VMAX® and VPLEX® storage arrays available from EMC Corporation of Hopkinton, Mass.

FIG. **12** shows an example method **1100** for managing host data of a set of hosts in a data storage apparatus. The method **1100** that may be carried out in connection with the data storage apparatus **116**. The method **1100** is typically performed by the software constructs, described in connection with FIGS. **1** and **2**, which reside in the memory **130** of the storage processor **110** and are run by the set of processors **124**. The various acts of the method **1100** may be ordered in any suitable way. Accordingly, embodiments may be constructed in which acts are performed in orders different from those illustrated, which may include performing some acts simultaneously, even though the acts are shown as sequential in the illustrated embodiments.

At **1110**, a layered operating stack is defined including a pool layer **232**, a file system layer **230**, a map layer **228** and one or more service layers **600**. The pool layer **232** defines and provides slices of the physical storage **180** for storing host data. The file system layer **230** includes one or more file systems **330** with respective files **601** stored in corresponding sets of slices Sx. The map layer **228** maps host objects to respective files **601** of the file systems **330**, where the host objects include block-organized logical units (LUNs) **310** and file-oriented host file systems (HFSs) **312** each in a corresponding original object form.

At **1120**, the pool, file system and map layers (**232**, **230** and **228**) collectively provide a basic data storage service in which a file **601** of a file system **330** is stored by distributing blocks **602** of the file **601** across the slices Sx in a manner maintaining the original object form and providing a basic level of storage efficiency, as described above in connection with FIG. **6**.

At **1130**, the service layer(s) provide one or more automated enhanced data services, each applying a respective service transformation to the original object form to generate respective data in a service-specified form and storing the data in the slices Sx. The service-specified form provides a service level of efficiency generally greater than the basic level of storage efficiency. Examples include a compression service **700** an deduplication service **740** that provide for greater storage efficiency, i.e., consuming less physical storage **180** for a given size host object. In another example, an automated storage tiering service **720** provides for efficiency in terms of a desired balance between storage efficiency and performance, as described above.

An improved technique has been described for a data storage apparatus that combines both block-based and file-based functionality in a unified data path architecture. The improved technique brings together IO processing of block-based storage systems and file-based storage systems by expressing both block-based objects and file-based objects in the form of files. These files are parts of an underlying, internal set of file systems, which are stored on a set of storage units served by a storage pool. Because block-based and file-based objects are all expressed as files of this set of file systems, a common set of services can be applied across block-based and file-based objects. Also, storage units released by any file or files of the underlying, internal set of file systems can be reused by any other file or files, regardless of whether the files represent LUNs, file systems, vVols, and so forth. Inefficiencies of stranded storage are thus greatly reduced or completely eliminated.

As used throughout this document, the words "comprising," "including," and "having" are intended to set forth certain items, steps, elements, or aspects of something in an open-ended fashion. Although certain embodiments are disclosed herein, it is understood that these are provided by way of example only and the invention is not limited to these particular embodiments. In addition, the word "set" as used herein indicates one or more of something, unless a statement is made to the contrary.

Having described certain embodiments, numerous alternative embodiments or variations can be made. For example, the lower-deck file systems **230** have been described as storing file representations of LUNs, host file systems, block-based vVols, file-based vVols, and snaps of any of the foregoing. These are merely examples, however. Other types of objects may be stored in the lower-deck file systems **230** as file representations, such as virtual hard disks (VHDs), virtual machine disks (VMDKs), internal file systems used by the data storage apparatus **116**, and internal volumes, for example.

In addition, as shown and described, different types of objects (LUNs, host file systems, etc.) are shown and described as being stored in respective lower-deck file systems. This is merely an example, however. Alternatively, any of LUNs, host file systems, block-based vVols, and file-based vVols, as well as snaps of any of the foregoing, may be included together in a single lower-deck file system or in any number of lower-deck file systems. Thus, it is not required that files representing different types of objects be stored in different lower-deck file systems.

Also, the improvements or portions thereof may be embodied as a non-transient computer-readable storage medium, such as a magnetic disk, magnetic tape, compact disk, DVD, optical disk, flash memory, Application Specific Integrated Circuit (ASIC), Field Programmable Gate Array (FPGA), and the like (shown by way of example as medium **1150** in FIG. **12**). Multiple computer-readable media may be used. The medium (or media) may be encoded with instructions which, when executed on one or more computers or other processors, perform methods that implement the various processes described herein. Such medium (or media) may be considered an article of manufacture or a machine, and may be transportable from one machine to another.

Further, although features are shown and described with reference to particular embodiments hereof, such features may be included in any of the disclosed embodiments and their variants. Thus, it is understood that features disclosed in connection with any embodiment can be included as variants of any other embodiment, whether such inclusion is made explicit herein or not.

Those skilled in the art will therefore understand that various changes in form and detail may be made to the embodiments disclosed herein without departing from the scope of the invention.

What is claimed is:

1. A data storage system, comprising:

a back-end interface to physical storage;

a front-end interface to a communications network coupling the data storage system to one or more host computers; and

one or more storage processors configured to execute computer program instructions to cause the data storage system to provide data storage services to the host computers using the physical storage by:

defining a layered operating stack including a pool layer, a file system layer, a map layer and one or more service layers, the pool layer defining and providing slices of the physical storage for storing host objects, the file system layer having one or more internal file systems with respective files stored in corresponding sets of slices of the physical storage, the map layer mapping the host objects to respective files of the one or more internal file systems, the host objects including block-organized host objects and file-oriented host objects, each of the block-organized host objects and the file-oriented host objects is in a corresponding original object form;

by the pool layer, the file system layer and the map layer collectively, providing a basic data storage service for storing a file of one of the one or more internal file systems by distributing blocks of the file across a set of slices of the physical storage, maintaining original object form of the stored file, and providing a basic level of storage efficiency; and

by the service layers, providing one or more automated enhanced data services, each automated enhanced data service applying a respective service transformation to the original object form to generate respective data in a service-specified form and storing the respective data in the slices, the service-specified form providing a service level of storage efficiency generally greater than the basic level of storage efficiency.

2. A data storage system according to claim **1**, wherein the basic level of storage efficiency and the service levels level of storage efficiency are respective levels of storage capacity usage efficiency, and wherein the service-specified form is of smaller data size than original object form.

3. A data storage system according to claim **2**, wherein the one or more automated enhanced data services include an automatic data compression service operative to apply data compression to each of one or more files of one of the one or more internal file systems to generate respective compressed forms of the one or more files.

4. A data storage system according to claim **3**, wherein:

the host objects are of a plurality of respective types selected from text and media;

the respective files for the host objects are accompanied by respective indicators of respective host object types of the host objects; and

the automatic data compression service is operative in response to the respective indicators of the respective host object types to apply respective distinct compression algorithms to the respective files to which the host objects of different host object types are mapped.

5. A data storage system according to claim **2**, wherein the one or more automated enhanced data services include an automatic data deduplication service operative to apply deduplication to blocks of one or more files of one of the internal file systems to replace duplicate data blocks with respective pointers to corresponding shared single instances.

6. A data storage system according to claim **5**, wherein a pool of the pool layer includes a deduplication container providing a single deduplication domain for the pool.

7. A data storage system according to claim **6**, wherein the single deduplication domain hosts a plurality of the files storing host objects of different types, a first file storing a block-organized host object, and a second file storing a file-oriented host object, the deduplication service applying deduplication across the host objects of different types.

8. A data storage system according to claim **6**, wherein the one or more automated enhanced data services further include an automatic data compression service to compress files in the deduplication container to further improve storage efficiency.

9. A data storage system according to claim **1**, wherein:

the slices of the pool layer are drawn from distinct tiers of the physical storage having respective storage usage efficiency and performance characteristics;

the one or more automated enhanced data services include an automated storage tiering service providing the service level of storage efficiency by automated and dynamic selection among the distinct tiers of the physical storage for the slices to achieve a desired balance of performance and storage usage efficiency.

10. A data storage system according to claim **9**, wherein the physical storage include magnetic disk drives and electronic flash drives each forming a respective tier, the magnetic disk drive tier providing a first storage density and first access time, the electronic flash drive tier providing a lower storage density and faster access time.

11. A data storage system according to claim **1**, wherein the block-organized host objects include one or more logical storage units (LUNs) and the file-oriented host objects include one or more host file systems, each host file system being stored in a single file of one of the one or more internal file systems.

12. A data storage system according to claim **1**, wherein the service layers are provided between the file system layer and the physical storage and operate upon the respective files of the one or more internal file systems for supporting both the block-organized host objects and the file-oriented host objects by operating on respective ones of the respective files that are mapped by the host objects.

13. A data storage system according to claim **12**, wherein the service layers include at least one of a first service layer and a second service layer, the first service layer provided between the file system layer and the pool layer and creating the service-specified form as service-specified content and organization of the slices as distinct from a basic content and organization of the slices, the second service layer provided between the pool layer and the physical storage and creating the service-specified form as service-specified mapping of the slices to the physical storage as distinct from a basic mapping of the slices to the physical storage.

14. A data storage system according to claim **1**, wherein data of each of the respective files of the one or more internal file systems is distributed across one or more respective sets of multiple fixed-size blocks, each set of multiple fixed-size blocks for a file being mapped to a respective one of the slices of the pool layer.

15. A method of operating a data storage system having a back-end interface to physical storage and a front-end interface to a communications network coupling the data storage system to one or more host computers, comprising:

defining a layered operating stack including a pool layer, a file system layer, a map layer and one or more service layers, the pool layer defining and providing slices of the physical storage for storing host objects, the file system layer having one or more internal file systems with respective files stored in corresponding sets of slices of the physical storage, the map layer mapping the host objects to respective files of the internal file systems, the host objects including block-organized host objects and file-oriented host objects, each of the block-organized host objects and the file-oriented host objects is in a corresponding original object form;

by the pool layer, the file system layer and the map layer collectively, providing a basic data storage service for storing a file of one of the one or more internal file systems by distributing blocks of the file across a set of slices of the physical storage, maintaining original object form of the stored file, and providing a basic level of storage efficiency; and

by the service layers, providing one or more automated enhanced data services, each automated enhanced data service applying a respective service transformation to the original object form to generate respective data in a service-specified form and storing the data in the slices, the service-specified form providing a service level of storage efficiency generally greater than the basic level of storage efficiency.

16. A method according to claim **15**, wherein the basic level of storage efficiency and the service level of storage efficiency are respective levels of storage capacity usage efficiency, and wherein the service-specified form is of smaller data size than original object form.

17. A method according to claim **16**, wherein the one or more automated enhanced data services include an automatic data compression service operative to apply data compression to each of one or more files of the one or more internal file systems to generate respective compressed forms of the one or more files.

18. A method according to claim **17**, wherein:

the host objects are of a plurality of respective types selected from text and media;

the respective files for the host objects are accompanied by respective indicators of respective host object types of the host objects; and

the automatic data compression service is operative in response to the respective indicators of the respective host object types to apply respective distinct compression algorithms to the respective files to which the host objects of different host object types are mapped.

19. A method according to claim **16**, wherein the one or more automated enhanced data services include an automatic data deduplication service operative to apply deduplication to blocks of one or more files of an internal file system to replace duplicate data blocks with respective pointers to corresponding shared single instances.

20. A method according to claim **19**, wherein a pool of the pool layer includes a deduplication container providing a single deduplication domain for the pool.

21. A method according to claim **20**, wherein the single deduplication domain hosts a plurality of the files storing host objects of different types, a first file storing a block-organized host object, and a second file storing a file-oriented host object, the deduplication service applying deduplication across the host objects of different types.

22. A method according to claim **20**, wherein the one or more automated enhanced data services further include an automatic data compression service files to compress the files in the deduplication container to further improve storage efficiency.

23. A method according to claim **15**, wherein:

the slices of the pool layer are drawn from distinct tiers of the physical storage having respective storage usage efficiency and performance characteristics;

the one or more automated enhanced data services include an automated storage tiering service providing the service level of storage efficiency by automated and dynamic selection among the distinct tiers of the physical storage for the slices to achieve a desired balance of performance and storage usage efficiency.

24. A method according to claim **23**, wherein the physical storage include magnetic disk drives and electronic flash drives each forming a respective tier, the magnetic disk drive tier providing a first storage density and first access time, the electronic flash drive tier providing a lower storage density and faster access time.

25. A method according to claim **15**, wherein the block-organized host objects include one or more logical storage units (LUNs) and the file-oriented host objects include one or more host file systems, each host file system being stored in a single file of one of the one or more internal file systems.

26. A computer program product having a non-transitory computer readable medium including instructions which, when executed by one or more storage processors of a data storage system cause the data storage system to provide data storage services to the host computers using physical storage, including:

defining a layered operating stack including a pool layer, a file system layer, a map layer and one or more service layers, the pool layer defining and providing slices of the physical storage for storing host objects, the file system layer having one or more internal file systems with respective files stored in corresponding sets of slices of the physical storage, the map layer mapping the host objects to respective files of the one or more internal file systems, the host objects including block-organized host objects and file-oriented host objects, each of the block-organized host objects and the file-oriented host objects is in a corresponding original object form;

by the pool, file system and map layers collectively, providing a basic data storage service for storing a file of one of the one or more internal file systems by distributing blocks of the file across a set of slices of the physical storage, maintaining original object form of the stored file, and providing a basic level of storage efficiency; and

by the service layers, providing one or more automated enhanced data services, each automated enhanced data service applying a respective service transformation to the original object form to generate respective data in a service-specified form and storing the data in the slices, the service-specified form providing a service level of efficiency generally greater than the basic level of storage efficiency.

* * * * *